

Managing the Aging Aircraft Problem

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Background

On April 28, 1988, multiple-fatigue cracks caused an Aloha Airlines Boeing 737-200 aircraft to lose part of its upper fuselage. Although the aircraft was able to land safely, the accident resulted in the death of one flight attendant and many passengers were injured. The aircraft, which entered service in April of 1969, had accumulated 35,496 hours and 89,690 flight cycles.

Though durability and damage tolerance were issues prior this, the Aloha accident is generally considered to be the start of the FAA's focused Aging Aircraft Program. Today more than a decade after the accident, it is fair to ask what has been done to prevent the recurrence of this kind of accident and what aging problems remain unsolved.

The First Decade

The first response to the accident was an industry-wide review of the adequacy of aircraft design and efficacy of maintenance programs. In general the aviation community found that with proper maintenance and structural modifications and with attention to service-related damage such as fatigue and corrosion, the service lives of airplanes could be safely extended. Airworthiness Directives (AD's) were issued to ensure that susceptible structure would not degrade below acceptable limits. These and other AD's also ensured proper attention to maintenance and inspection.

To address mid- and long-range issues, the industry established the Aging Aircraft Task Force (now the Airworthiness Assurance Working Group, AAWG). The FAA established the National Aging Aircraft Program and the National Aging Aircraft Research Program. Over the last decade these organizations and their government and industry oversight have sought to identify and rectify all issues associated with the operation of aircraft beyond their design service objectives.

In 1993 the AAWG report, *Structural Fatigue Evaluation for Aging Airplanes*, identified 14 multi-site damage(MSD)/multi-element damage(MED)-susceptible structural details to be evaluated and monitored. Though the lap splice implicated in the Aloha Accident would remain the top priority, there were now potential widespread fatigue damage (WFD) threats that would keep engineers and scientists busy into the foreseeable future. In fact, the lap-splice problem itself managed to present new failure modes (top row and inner-layer cracking) before old ones were fully resolved.

In 1999 the AAWG report, *Recommendations for Regulatory Action to Prevent Widespread Fatigue Damage in the Commercial Airplane Fleet*, added additional structural details to those of earlier concern. That report did not, however, simply augment the problem with new issues – it contained industry recommendations for addressing the problem. Those recommendations affect the content of upcoming FAA rules and advisory material. Though the new rules and advisory material will not present explicit solutions for WFD, they provide a roadmap for engineers to solve specific WFD problems.

During this first ten years FAA researchers focused their efforts in three technical areas: fatigue and fracture, nondestructive inspection, and flight loads. Efforts in the area of flight loads provided the necessary foundation for accurate assessment of internal loads and finally local stresses. Though essential to the development of a complete solution to aging structures problems, its application to aged aircraft did not differ in any substantial way from loads monitoring programs supporting validation of new designs.

Research in fatigue and fracture concentrated on fundamental issues associated with crack initiation, crack growth, and residual strength of multisite-damaged fuselage skins. Working in conjunction with National Aeronautics and Space Administration and the US Air Force, the FAA developed fast and efficient crack growth models, and accurate predictive capability for residual strength in the presence of MSD. Progress has been made in the areas of crack initiation and small crack growth, but predictive modeling of these phenomenon still eludes us.

Research in inspection technologies prioritized the development of technologies to identify cracks characteristic of multi-site damage, but other tasks included development of corrosion and disbond detection technologies. Though laboratory prototypes have shown sensitivity well beyond that of systems typically available to aircraft inspection technicians, implementation as cost-effective, commercially available devices is not always achieved.

Beyond Large Transport Structures

Though the Aloha accident was the impetus for the FAA's Aging Aircraft Program, forward-looking management used the opportunity to identify and address potential problems before they could emerge as true threats to aviation safety. In particular, the FAA concluded that improvements to the management of large commercial transports should be leveraged to initiate similar improvements in the management of commuters and helicopters. At the time of the Aloha accident neither class of aircraft utilized the more sophisticated damage tolerance concept for design and maintenance.

Much of the work in the area of commuter damage tolerance involved the relatively straightforward application of large transport damage tolerance concepts to commuter aircraft. Rotorcraft, however, present some additional challenges. Because of their very different utilization profiles (unpressurized, short-duration flights at low altitude) and because of their exposure to high-cycle fatigue (associated with rotor dynamics), the application of damage tolerance to rotorcraft requires additional research and development.

Unfortunately not all issues would receive appropriate attention prior to the occurrence of a catastrophic accident. In 1989 the fan disk on the number two engine of a DC10 disintegrated resulting in loss of all hydraulics. The pilots managed to crash land the aircraft saving 171 of the 282 passengers and crew. The accident resulted in the establishment of the Titanium Rotating Components Review Team and subsequently the Engine Titanium Consortium (ETC). Since its start, the ETC has managed to improve billet inspection sensitivity by a factor of 4 and has made substantial improvements in the techniques used for in-service inspection.

In the summer of 1996 a TWA B-747 exploded over the Atlantic shortly after take-off from New York's Kennedy Airport. The National Transportation Safety Board determines that the probable cause of the accident was an explosion of the center wing fuel tank resulting from ignition of the flammable fuel-air mixture in the tank. The source of ignition energy for the explosion could not be determined with certainty but, of the sources evaluated by the investigation, the most likely was a short circuit outside of the fuel tank that allowed excessive voltage to enter it through electrical wiring associated with the fuel quantity indication system.

As a result non-structural systems will be a major thrust of the continuing National Aging Aircraft Research Program.

Remaining Challenges for Structural Integrity

Structural integrity issues for aged aircraft are particularly difficult because the damage under consideration consists of multiple interacting flaws and the cracks sizes are often in a range where the phenomenon is complex and not well behaved. To address the problem, sophisticated three-dimensional non-linear crack-growth models are required. These models must be efficient enough to allow the consideration of multiple interacting cracks – perhaps in a probabilistic fashion. In addition to the need for the enhancement or development of sophisticated

computational models, there remains a need for research that is more applications oriented, to extend existing methods and procedures to new applications or areas.

Damage Tolerance Methods: Because damage tolerance methodology has been extensively and successfully used for large transport aircraft structures, the FAA recently completed rulemaking to extend the concept to commuter aircraft, and is now initiating a research program to develop damage tolerance methodologies for rotorcraft. Research efforts include the development of fracture mechanics methodologies, precise usage spectrums, and enhanced non-destructive inspection tools. Other related research efforts include the validation of a database of rotorcraft accidents, a cross-reference study of accident causes and regulatory actions, and a review of existing AD's and guidelines for composite replacement of metallic dynamic components with composite parts. Within the next five years, the FAA plans to revise the Federal Aviation Regulations to require damage tolerance assessment criteria.

Planning has just begun for a similar effort to implement damage tolerance requirements for propellers. Propellers have been exclusively designed and certified using the safe-life approach. Generally, safe-life is experimentally determined using the mission profile, flight loads, S-N data, and Miner's cumulative fatigue damage rule. The FAA is planning to initiate a rulemaking process to implement damage tolerance requirements for propellers. The research supporting this rulemaking will leverage and build upon the rotorcraft damage tolerance research project.

Destructive Assessment of Decommissioned Aircraft: The destructive testing and analysis of structure removed from retired aircraft will provide the FAA with first hand knowledge of teardown procedures conducted in support of applications for continued airworthiness certification. Experience and knowledge gained from this destructive analysis will enable the FAA to issue essential rules, policy, and advisory circulars pertaining to the prevention of WFD. Data from this effort will be used to validate methods for predicting the onset of multiple site damage (MSD). This research will also provide data that can be used to evaluate the efficacy of standard and emerging inspection technologies.

The planned research includes in-house testing of sections removed from retired aircraft to compare the fatigue performance of aged aircraft structure with that of fabricated components subject to only laboratory testing. Current plans include investigating both the fuselage and wing structures. Post-test fractography will substantiate crack growth model and rate data.

Material Properties Standardization: In partnership with the United States Air Force the FAA will continue to support material properties standardization efforts and expand these to include fracture properties. The existence of a standardized process for establishing statistically based allowables that comply with 14 CFR 23/25/27/29.613 ensures both the adequacy of design and efficiency of the certification process. Expanded implementation and enhancement of the process will allow manufacturers to employ new materials (including fastening systems) with superior performance characteristics.

The planned research includes establishing a baseline set of fracture mechanics properties, (e.g. crack growth rate and plane strain fracture toughness, K_{Ic} , crack resistance, stress corrosion cracking, K_{ISCC}) that can be used and referenced with confidence in performing, reviewing, and approving damage tolerance evaluations. Research will include stress-intensity factor development and verification, as well as the generation of two and three-dimensional fracture parameters for aircraft structure.

Crack Initiation and Small Crack Growth: Although there has been research in this area, a complete understanding of the crack initiation phenomenon has yet to be reached. Further research is required to predict crack initiation from such structural details as rivet holes. Areas that need further research are the development of equivalent initial flaw size data for all alloys and geometries, development of small crack growth rate data for specific materials, and the determination of scatter in the initiation of MSD/MED for different structural configurations.

Alternate Structural Forms: Damage tolerant design and the concepts of fail safety are well established for legacy structure in use for many years. Now, however, aircraft manufactures are pursuing materials and fabrication techniques to reduce part count and fabrication expense. Among the new designs being considered are integrally stiffened structures and precision castings.

In order to take advantage of these new materials and fabrication techniques, designers must show damage tolerance and/or fail-safety. This requires a better understanding of how cracks develop and grow in these designs and which inspection techniques are capable of ensuring the absence of critical flaws.

Remaining Challenges for Inspection

Though novel technologies involve some of the most exciting science and engineering, they are also the most problematic to manage. Focusing on the technical possibilities may be personally satisfying for the technology enthusiast, but will often lead to impractical solutions to real problems or solutions to non-existent problems. The management challenge is to identify application potential. Some of the things to consider in this regard are:

an aging commercial fleet: Aircraft were designed to be inspected visually, but certification testing and service experience often results in specific directed inspections. The requirement for these directed inspections may be established at the aircraft's time of introduction to service (as a certification maintenance requirement), but more likely are the result of service experience. As the aircraft ages these inspections become increasingly more problematic: inaccessible areas, multiple failure modes, and unique structure all complicate the inspection. Many of these inspections will be even more difficult if the repeat interval forces operators to perform the inspections at other than a regularly scheduled heavy maintenance check.

widespread fatigue damage: Aircraft susceptible to potential WFD pose a substantial threat to safety, yet the identification of conditions possibly leading to widespread fatigue damage is not at all straight forward. Though the precise risk of WFD to aircraft is the subject of continuing research, it is fairly clear that, for an equivalent level of risk, critical crack lengths are larger for structure with discrete damage than for structure with MSD, MED and other WFD precursors.

regulatory requirements: The Federal Aviation Regulations regarding the detectability and detection of damage on aircraft are rather precise and may not allow the timely application of an "improved" inspection. Inspection technology must be validated with respect to the prevailing damage tolerance philosophy for airframes and the safe-life philosophy for engine components.

organizational/operational constraints: Operators schedule inspection and maintenance to optimize safety, maximize utilization, and minimize overall maintenance/operational costs. Focusing on only the cost of the inspection can lead to faulty conclusions regarding the practicality of an emerging technique.

technology plums: Every once in a while a technology comes along with features so appealing that we are compelled to make larger changes to accommodate that technology. It has been our experience that system developers have unrealistic expectations of this potential.

Cognizant of these factors, FAA sees great promise in two broad classes of inspection techniques: rapid imaging inspection and distributed damage assessment.

Rapid Imaging Inspection: Rapid imaging inspection may be the next substantial change in airplane inspection practice. Inexpensive computational power (for data processing and display) and increasingly long and complex inspection tasks may foster the near term implementation of such techniques.

As we approach the fundamental limit on the signal to noise ratio for a given technology, to improve inspection capability we must either identify new technologies unconstrained by this limit or relax our requirements on the signal to noise ratio. By applying scanning technologies in conjunction with an existing technique we can generate data that allows us to reliably detect flaws just above the noise floor. This is accomplished by supplementing signal to noise criteria with subjective and objective pattern recognition criteria.

One intriguing technique for broadfield detection of cracks is thermosonics, a combination of ultrasonic excitation and thermal signature identification. The technique works by identifying the friction heating of crack interfaces subject to ultrasonic excitation. Thermal images of cracked parts subject to ultrasonic excitation appear much like the indications seen during a fluorescent penetrant inspection. Though potentially sensitive to very small cracks the correlation of flaw size to signal strength is not a simple relationship – presenting problems to the engineer who might need to specify a minimum detectable crack.

Distributed Damage Detection: Distributed damage detection is the detection of structural degradation by indirect means that indicate (but do not necessarily isolate or characterize) damage. An inspection device might, for instance, be sensitive to unusual structural deformation indicating altered load paths or elastic properties.

Acoustic emissions (AE) was perhaps the first technology to challenge our typical inspection paradigm. Though claims have been made regarding the ability of AE to locate and characterize cracks, their real virtue is probably their sensitivity to the cumulative presence of active cracks somewhere in a localized area of the structure. Eddy current is no more sensitive to isolated cracks than to a crack associated with widespread fatigue damage. AE (when it works) should be more sensitive to multiple cracks than individual cracks since crack growth is probabilistic in nature and does not necessarily produce the optimal signal for AE on each load cycle.

Other emerging techniques challenge our inspection paradigm in different ways. Residual stress measurements tell us something about the stress state of a component without telling us about the individual flaws which might exist in the component. Though our common sense and experience tells us that this information is useful, it is hard to see how it could fit into a damage tolerance philosophy of airworthiness, which focuses on discrete flaws. Such techniques could be used to screen-out bad components, but cannot be used to verify the airworthiness of good components. The application of such technology to safe-life parts does not raise such concerns, but most safety-critical safe-life parts (e.g. engine disks) are life-limited without consideration of the beneficial effects of residual stress.

One FAA-sponsored technology which may change inspection practice is non-relative eddy current (for lack of a better name). Systems such as Jentek's Meandering Winding Magnetometer (MWM) probe may be able to identify conductivity changes in components which may in turn be indicative of a distressed state. Though such information would probably not alleviate the need for a more conventional inspection for discrete flaws it could help inspectors determine whether a series of flaws is a series of isolated flaws or a condition indicative of widespread fatigue damage.

Because many of these techniques are not directly sensitive to discrete flaws, most present applications are non-critical. In fact, AE is used extensively in monitoring fatigue tests. MWM may find a similar application in monitoring coupon, component, and full scale tests, before it becomes a widely accepted in-service inspection tool.

Emerging Challenges

Revision A of the AAWG report, *Recommendations for Regulatory Action to Prevent Widespread Fatigue Damage in the Commercial Airplane Fleet*, included for the first time a new potential WFD threat – fillet cracking. In-service inspections of 737 aircraft showed that chemically-milled fuselage skins showed signs of multiple-site cracking along the fillet radius. In some cases the cracks had linked-up into cracks up to 8 inches in total length.

The nature of this cracking poses new challenges for both modeling and detection: The cracking is very different from rivet cracking in that 1) there are no discrete initiation sites (i.e. rivet holes) and 2) the problem is known to cluster around certain line numbers and not others. Modeling of this phenomenon first requires a metallurgical understanding of the initiation mechanism, rate, and spatial distribution. This information will serve as the basis for crack growth and link-up models similar to those for rivet site cracking. More complex will be the risk assessment associated with an infinite set of initiation sites.

If the target crack size is small, detection of such cracking may require more sophisticated techniques than those commonly used for inspecting rivet site cracking. Because the potential initiation sites are distributed over an invisible line on the fuselage exterior, imaging techniques may be necessary. If the damage is sufficient diffuse techniques such as Jentek's MWM may provide early indication weakened structure.

But by far the most challenging problem of aging involves not metal but polymers.

Failures of aircraft electrical systems – principally power wires – have the potential to both degrade aircraft performance and cause catastrophic in-flight fires. Since the 60’s five major wire types have been used as general-purpose wire: PVC/Glass/Nylon, Poly-X, ETFE, Polyimide, and composite.¹

PVC/Glass/Nylon and Poly-X are obsolete but remain prevalent in aged aircraft. Polyimide has excellent fire resistance but suffers from a propensity to arc violently with the potential to damage multiple systems or cause fire. XL-ETFE appears to age well and does not arc-track, but it is more susceptible to traumatic damage and less resistant to fire than polyimide. Composite wire appears to offer all of the virtues of polyimide and XL-ETFE without their deficiencies. However, composite wire types have not been in service long enough to proclaim their ultimate superiority over their predecessors.

Though much progress has been made in identifying and mitigating wire shortcomings, a very large population of polyimide wire will reach twenty years of age in the next several years. Figure 1 shows wire type usage for various aircraft from 1960 through the present. If we do not fully understand the degradation characteristics of this wire and put in place programs to eliminate or mitigate failure associated with this degradation, aircraft operators may – in the event of a severe failure trend – be forced to take drastic action on their fleet of polyimide-wired aircraft.

Mechanical systems may also present aging challenges though a trend analysis of the FAA’s Service Difficult Reports did not immediately point to impending problems with any particular class of mechanical systems.² An

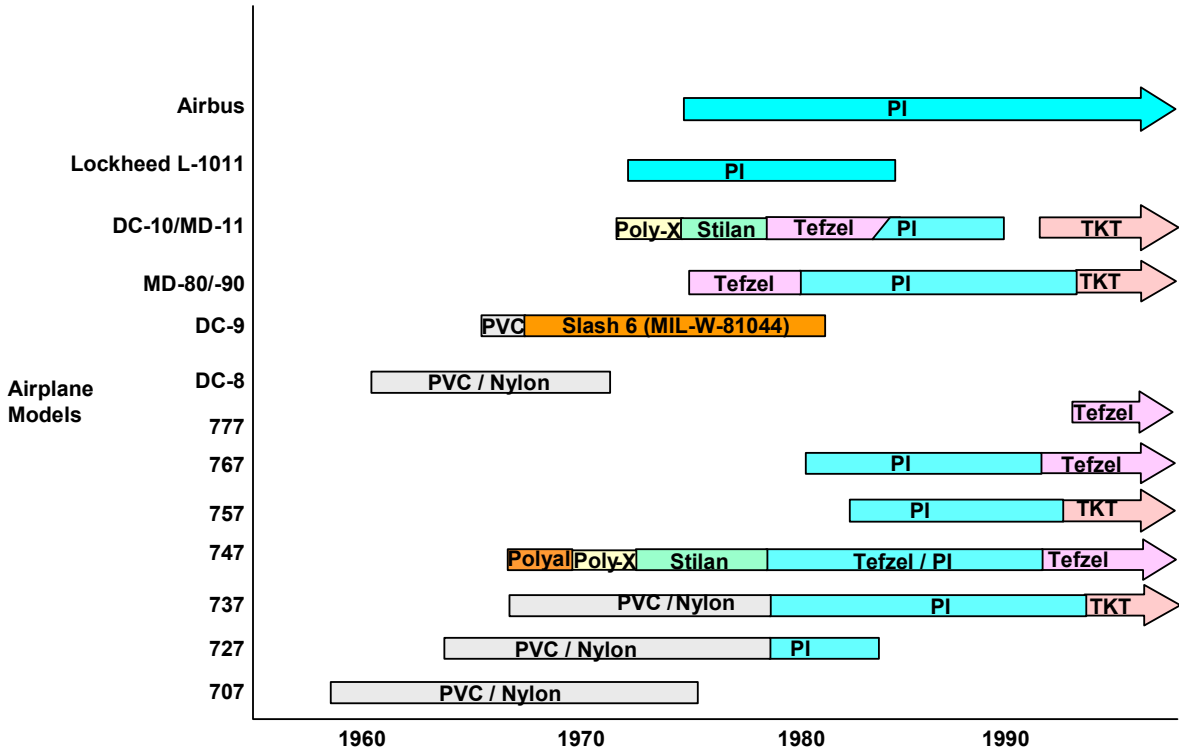


Figure 1: Wire Utilization

examination of revenue service aircraft and service records did, however, uncover a potential problem with uninspectable, dual-element flight control linkages. In theory these mechanisms are fail-safe because an obvious failure of the primary load path will not result in failure of the mechanism. This rationale, however,

¹ Stilan was also used but is very rare in the current fleet of transport aircraft. Other special purpose wire types are used for specific applications such as high temperature resistance.

² An Analysis Of The Service Difficulty Reports Database To Determine The Significance Of Mechanical Systems Degradation, Presented To ATSRAC, June 7, 2000

does not consider the potential for advanced degradation of the secondary load path (through corrosion, for example) or simultaneous degradation of both elements, possibly resulting in simultaneous failure.

The FAA's risk assessment projects for electrical and mechanical systems will identify other potential aging systems issues.

Business Within a Performance Based Organization

Though the nature of the work in aging aircraft research program has evolved gradually since the start of the program, the measure of its progress has undergone a revolutionary change. The Government Performance and Results Act (GPRA) of 1993 mandates that for any government project there be clear statements of intended outcomes and outputs (services and products). The GPRA further mandates that performance indicators be established and utilized in evaluating government programs. As a result of this act, the National Aging Aircraft Research Program was recast as a goal-oriented program supported by a performance-based organization.

As the aviation industry advances into the next millennium, the FAA is committed to some very aggressive safety goals – an 80% reduction in the fatal accident rate over 10 years. This safety goal is driving aircraft research – and specifically aging aircraft research – toward more probability-driven approaches to aircraft life management. Research efforts must show direct potential for accident reduction (or mitigation) and must be prioritized in terms of their expected return on investment – lives saved.

This new business model argues for risk-based approach to the establishment of certification and maintenance requirements. For systems the issue is straightforward: If systems reliability is to carry its fair share of the five-fold reduction in accident rates, then there must be a five-fold decrease in the 10^{-9} reliability metric of FAR 25.1309. Technical challenges remain, but the regulatory foundation exists.

For structural failure the issue is more complex. Other than measuring our current effectiveness against accident and incident data, there is no accepted means of quantitatively assessing the risk of structural failure.

Furthermore accepted interventions such as requiring two inspection opportunities with at least 90/95 percent probability of detection prior to critical crack growth, bound – but do not identify – the risk. This can only be remedied by a more rigorous probabilistic based approach to flaw initiation and growth modeling and inspection probability of detection. In particular:

- Crack initiation and distribution should be considered a random variable modeled by some appropriate distribution. Treatment of flaw initiation as a worst-case deterministic scenario (i.e., considering only a single point on the tail of the distribution as representative of all flaw initiation) could lead to either impractical design (being too far out on the tail) or under-assessed risk (being too far in on the tail).
- Flaws detection must be quantified not just in terms of a system's ability to identify arbitrary features of a flaw, but in terms of its ability to detect and quantify structural degradation. For individual cracks the issue has been relatively easy: Crack length is a direct indicator of structural degradation (at least for through-cracks). For MSD the size of any individual flaw is only a partial indication of degradation. A more appropriate measure of risk in this situation would be an assessment of the probability of identifying the presence and severity of the MSD. This might, for instance, entail the probability detecting the first crack, followed by the probability of detecting a sufficient number of other cracks (a conditional probability), followed by the probability of correctly predicting what might have gone undetected.

If the aviation community does move toward objective measures of risk, it is likely that the change will be gradual and evolutionary. The current safety record of both commercial and military operators is a tribute to those who struggled to put it in place and should not be tampered with lightly.

Concluding Remarks

Though great progress has been made in the area of aging aircraft, the continued desire to maintain aircraft in revenue service beyond their design service objectives will almost certainly result in new structural integrity and systems reliability problems. It is the mission of the FAA's Aging Aircraft Program (or perhaps more appropriately the Continued Airworthiness Program) to ensure that age-related problems are predicted and eliminated or mitigated prior to their having a major impact on safety.